SOME EFFECTS OF CAPILLARITY ON OIL ACCUMULATION[1]

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All rocks in the upper crust of the earth contain pore space. The percentage by volume of this space varies from a fraction of 1 per cent in the case of most fresh crystalline rocks[2] up to 40 per cent in some sandstones.[3] Below ground-water level these openings are more or less saturated with water, which moves about from points of higher to points of lower pressure.

The movement of water thus entombed does not exactly follow hydrostatic laws, as can be observed by the small loss of head in artesian flow. For example, an instance is cited by Van Hise[4] where water traveled under ground 150 kilometers with a loss of only 50 m. in head. This shows that the movement was very slow (perhaps a few feet per year), for the friction through the porous stratum was almost nothing. In the case of water moving in large openings, such as pipes, friction is an important factor. A somewhat similar example was observed by the author in Missouri, where the loss of head by flow in the Roubidoux sandstone was about 200 ft. in 75 miles. A theoretical means of comparison with the observed facts is to note the size of the openings in the rocks. All tubular openings less than 0.508 mm.[5] are capillary. Therefore, by geometrical proof, it can be shown that sandstones with uniform rounded grains of less than 2 mm. in diameter, would contain mainly capillary openings. Rocks with uniform rounded grains, regardless of the size of grain, contain about the same

[1] A paper read before the Geologic Conference of Oklahoma, January 7, 1916, at Norman, Oklahoma.

[2] Van Hise, *Monograph, U.S.G.S. 47*, p. 125.

[3] G. P. Merril, *Rocks, Rock-Weathering and Soils*, p. 198.

[4] *Monograph, U.S.G.S. 47*, p. 587.

[5] Alfred Daniell, *Text Book of Physics*, p. 315.

amount of pore space, and this is greater than in rocks which have varying-sized and angular grains. Most rocks are made up of particles irregular in shape and less than 2 mm. in diameter, consequently the movement of underground water must be greatly affected by capillary action, *and evidently the forces of static capillarity must be overbalanced before movement can take place.* For that reason a discussion of Poiseuille's law of flow in capillary tubes has been omitted, and the conditions of static capillarity are thought to be of *first importance.*

The phenomenon of capillarity—that of a column of liquid rising or being depressed by a small opening—is due to two causes: (1) the surface tension of the liquid, and (2) the fact that the material of which the tube is composed has a greater or less adhesion for the liquid than the cohesion of the liquid itself.

Surface tension is the force at the surface of a liquid, which tends to make the liquid contract, and can be expressed by the following formula:

$$a) \qquad T=\frac{\pi r^2 hqg}{2\pi r \cos a},$$

where r equals the radius of the tube; h, the height of liquid standing in the tube; q, the density of the liquid; g, the acceleration of gravity; and a, the angle of contact between the liquid and the tube.

Surface tension is a linear function of the absolute temperature,[1] and that for water can be expressed by:

$$b) \qquad T=0.21(370-t)$$ [2]

where t equals the temperature Centigrade.

Pressure causes some change in surface tension, but presumably small. "For changes in the properties of water induced by pressure of, say, 1,000 atmospheres are usually similar in magnitude and direction to those observed when a relatively small quantity of a salt is dissolved in it; and the surface tension of such dilute (0.5 N or less) solutions differs by only a small percentage from that of pure water."[3]

[1] Knipp, *Physical Review*, XI, 151.

[2] Johnston and Adams, *Journal of Geology*, XXII, 9.

[3] *Ibid.*

Different substances have different surface tensions, which can be calculated by means of formula a) with the necessary observed factors. For instance, crude oil at 20° C. has an average surface tension of about 25 dynes per cm.;[1] water at 18° C. about 75 dynes; and mercury at 20° C. about 540 dynes.[2]

Surface tension also varies with the nature of materials in surfacial contact. For instance, the surface tension of mercury when in contact with water is different from when in contact with air. Unfortunately, a number of such different values are not recorded, so that this discussion is limited to liquids in contact with air.

It is necessary that the adhesion of the material in the tube be either greater or less than the cohesion of the liquid, otherwise there would be no chance for surface tension to display itself. When adhesion is less than cohesion, depression in the liquid results, as in the case of mercury and glass; when adhesion is greater than cohesion, there is a rise in the capillary tube. If adhesion greatly overbalances surface tension, the liquid surface may break and the liquid mount up the sides of the vessel, as in the case of some light oils in a low porcelain cup. Consequently, before one liquid will replace another in capillary openings the replacing liquid must not only have a greater surface tension but also a greater adhesive power for the material of which the tube is composed.

Capillary force according to equation a) is a function of surface tension, contact angle, diameter of pore space, density of liquid and acceleration of gravity. In the case of water-air surface the contact angle is 0, therefore ($\cos a$) equals 1; the density of water is 1; so the equation resolves itself into:

$$h=kT/r,$$

where k equals 0.00204.

Starting with a temperature of 15° C., at a depth of 100 m., the capillary pressures shown on p. 801 are computed from the above formula. Pressures are recorded in kilograms per square centimeter.

The following calculations show, first, that capillary pressures decrease with depth on account of the increase in temperature;

[1] Washburn, *A.I.M.E.*, L, 831.

[2] Tait, *Properties of Matter*, p. 264.

secondly, that above 750 m. capillary pressure in openings of 0.01 micron is greater than the combined rock and hydrostatic pressures; therefore capillarity is most important in the upper 3,000 ft. of the earth's crust; and thirdly, that above 5,000 ft. one liquid of greater surface tension and adhesion for the tube material should readily replace a weaker liquid in small openings; or in other words, the liquid of less surface tension should be concentrated in the larger openings.

CAPILLARY PRESSURES UNDER VARYING CONDITIONS*

Depth Meters†	Hydrostatic Pressure	Capillary Pressure for Pore Diameter of		Rock Pressure	Hydrostatic and Capillary Pressures
		100Mc	0.01Mc		
100........	10	.03	306	27	316
500........	50	.03	294	135	344
1,000........	100	.027	278	270	378
2,000........	200	.025	250	540	450

* Johnston and Adams, *op. cit.*, XXII, 13.

† An increase of temperature of 1° for every 30 m. was used to obtain these results.

Capillary phenomena can take place in openings of 0.01 micron, as shown by Bakker,[1] where he concludes that the minimum size of capillary openings is a few times the diameter of the molecule. According to Whitney,[2] mud contains more than 10,000,000,000 particles per gram. If these were perfectly round particles, so that the pore space could be a maximum, the diameter of the individual would be about 3 microns. Therefore the maximum openings would be about 0.5 micron. Clay used in the following experiments was made up of particles which varied from 1 to 5 microns in diameter, as measured by a microscope. The openings then at a maximum would be a fraction of a micron. Now, since the openings in mud are evidently less than 1 micron by both of the above methods of approach, it has been assumed for the following hypothetical problem, that in compressed shales where the particles are not round nor of equal size the openings are diminished to 0.01 micron.

[1] *Zeitschrift für physikalische Chemie*, LXXX, No. 2, 129.

[2] *U.S. Dept. Ag., Weather Bureau, Bull.* 4, p. 73.

Capillary pressure of 300 atmospheres means that water will enter the pore spaces above static water level until the pressure in the pore tubes, due to the weight of the column of liquid above or otherwise, is equivalent to 300 atmospheres pressure; or that, if the water is held back by a gas or liquid of less surface tension, it will accumulate a pressure in the said gas or liquid proportional to the difference in capillary pressures for that temperature and size of opening.

The following assumptions have been made for a hypothetical problem: (1) there exists a cavity or series of connected openings, larger than 0.5 mm., under a strip of rock 10,000 ft. wide and 1,000 ft. thick. The openings in the rock above are as small as 0.01 micron, and filled with water; (2) the material below the cavity is an oil shale in which the openings are 0.01 micron, and that water is in the lower part of this shale under sufficient head to make it rise to the level of the bottom of the cavity.

The water will drive the oil into the open cavity with a pressure equal to the difference in the capillary pressures of oil and water for that size of opening. This amount for the given temperature of 15° C. and openings of 0.01 micron is approximately 200 atmospheres, or about 400,000 lb. per sq. ft. The weight of the rock column above is approximately 150,000 lb. per sq. ft.; and that of the full water column would be less than 62,000 lb., because the column cannot possibly act upon a full square foot, but only upon the area of pore space, for convenience say 50,000 lb. Now the resultant pressure upon the rock above the cavity is 400,000 minus (150,000 plus 50,000), or 200,000 lb. per sq. ft.

This pressure acts as upon a beam fixed at both ends. The capillary water above prevents the rising of the oil into the rock, but in turn affords no downward pressure on the oil in the opening, other than the weight of the hydrostatic column, as has been accounted for in the above assumptions.

The deflection for a beam fixed at both ends with a uniform load may be expressed by the following formula:

$$d=\frac{wl^4}{384EI},$$

where d is the deflection; w, the uniform load; 1, length of beam; E, the modulus of elasticity; and I, the moment of inertia.

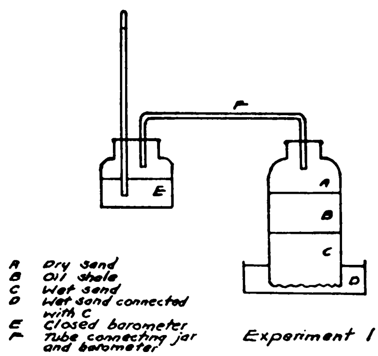
Substituting the values for a beam of rock 10,000 ft. wide, 1,000 ft. deep, 1 ft. broad, with E equal to 6,000,000 lb. per sq. in. (the value of granite), and I equal to $bh3/12$ or $(1{,}000)3/12$, the equation resolves itself into the following:

$$\frac{200{,}000 \times 10{,}000 \times 10{,}000 \times 10{,}000 \times 10{,}000 \times 12}{384 \times 6{,}000{,}000 \times 144 \times 1{,}000 \times 1{,}000 \times 1{,}000}$$

or approximately 72 ft. This means an anticline with a dip each way from the crest of about 1 degree.

Experiment 1

Statement.—An open glass cylinder (3 in. in diameter, and 8 in. in length) was placed in a pan of wet sand, so that the sand filled the lower one-third of the cylinder. The water had free access from the sand in the pan to the sand in the cylinder. Then a layer of oil-saturated mud was placed in the cylinder upon the wet sand; this mud occupied about one-third of the cylinder and was above the level of the water in the pan. The cylinder was then filled with dry sand, and the top sealed with a tube attachment to a closed barometer. Readings of the mercury were taken before sealing and compared with a standard barometer in the same room.

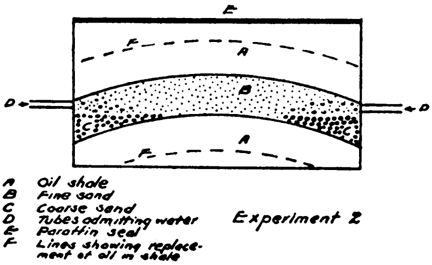


Results.—The water migrated upward about 1 cm. into the mud and the oil moved about the same amount into the dry sand. The mercury had risen within 24 hours, about $2\frac{1}{2}$ cm. over the atmospheric pressure as compared with the barometer; it then remained stationary. The oil also migrated down into the wet sand and collected in some of the larger openings.

Experiment 2

Statement.—A ($\frac{3}{4}$-in.) layer of wet sand was placed between two layers of oil in a (8 in.$\times$4 in.$\times$4 in.) rectangular glass box. The sand layer was arranged in an arched manner so that the artificial anticline dipped about 30 degrees to either side. The sand grains in the top of the curve were small (all passing a 40-mesh sieve), while those in the troughs were comparatively coarse (none passing a 10-mesh sieve). The top was sealed with paraffin and water

was allowed to enter the box through openings at the lowest horizon of the sand. This water level was never as high as the top of the curve in the sand.

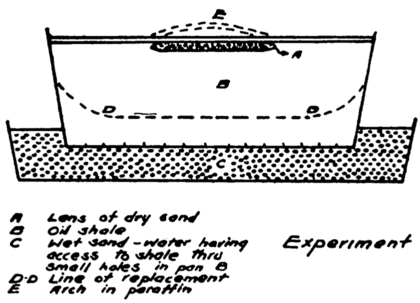


Experiment 2

Results.—The water entered the mud in both directions from the sand layer and replaced about an inch strip of the oil in the mud. The oil moved into the coarser grains of sand and within 24 hours there was an oil pool in both synclines on either side of a water-filled anticline. Later, the oil began to move out of the openings which admitted water from the outside, and collected upon the surface of the water.

Experiment 3

Statement.—A (3-in.) layer of oil mud was placed in a (round 14-in. diameter) pan, which had a number of small holes in the bottom. A circular lens of dry sand (3 in. in diameter and ½ in. thick) was fitted down in the center at the top of the mud. The surface was leveled as carefully as possible and covered with a ¼-in. layer of paraffin. This pan was then set in a pan of wet sand, so that the water level stood about 1 in. below the top of the mud in the first pan.



Experiment 3

Results.—After two weeks the paraffin had arched up over the dry sand, with a maximum rise of ⅜-in. The paraffin was punctured at this point, and within 24 hours the oil began to seep out and slowly run down the side of the dome. Several days later, seeps began to come out at various places, where the oil had dissolved its way through the paraffin. The oil also passed down out of the holes in the bottom of the pan through the sand, and collected upon the surface of the free water over the sand. Upon examination, the water had replaced about 1½ in. of the oil in the bottom of the pan.

In the foregoing experiments, the mud was made from a mixture of dried clays, the particles of which measured from 0.005 to 0.001 mm., and Oklahoma crude oil (38 Baumé). Enough oil was used to make the mud pack well.

Conclusions

At the time of this reading only the results of the elementary experiments can be given. This paper does not attempt to say that capillary forces have ever caused anticlines in nature, but merely points out that possibility. At least one thing is borne out by the above experiments: that the segregation of oil and water in openings of the ordinary oil rocks is not according to the general hydrostatic idea, but that the water forces the oil into the larger openings regardless of elevation or structure. This does not do away with the general anticlinal theory of accumulation. On the contrary, it substantiates this theory, as the larger openings are more often in the crest of the anticline, regardless as to whether the oil caused the fold or whether the oil migrated there after the fold had been made.